LONG BASALTIC LAVA FLOWS OF THE MT ROUSE VOLCANO IN THE NEWER VOLCANIC PROVINCE OF SOUTHEASTERN AUSTRALIA

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Mt Rouse is a complex scoria and lava volcano situated 250 km west of Melbourne, in the Western Plains subprovince of the Newer Volcanic Province of Southeastern Australia. The basaltic lava flows of Mt Rouse have travelled southwards a distance of 60 km and extend to the present-day coast at Port Fairy. The flows branch and rejoin, and pass through narrow pre-existing valleys less than 100 m wide, providing one of the best examples of long lava flows in Western Victoria. The 'stony rise' topography of the flows indicates that lava sheet inflation and associated lava tube systems were the mechanisms for long lava flow development.

Detailed field work, including Regolith Terrain Unit mapping of the region, indicates a single source for all the flows, allowing a reassessment of the age of the flows. K/Ar dates of about 0.32 Ma from lava 15 km south of the volcano, and about 0.3 Ma from near Port Fairy, give the age of the activity, which is exceptional in having an estimated volume some three times the average of other large eruptions in the Province.

Key words: volcano, basaltic, lava, long flow, age of eruption

THE NEWER Volcanic Province (NVP) covers an area of 15 000 km^2, and has nearly 400 points of eruption of Pliocene to Recent age. It includes the Western Plains subprovince, known locally as the Western District, with extensive lava fields and some 100 or so eruption points (Ollier & Joyce 1964), as well as areas of more concentrated activity in the Western Uplands subprovince, the eastern Uplands subprovince, and smaller areas in the Mt Gambier subprovince across the border in Southeastern South Australia.

The Western Plains subprovince is characterised by gently undulating plains, with many small pyroclastic cones that rarely reach more than 200 m above the general level. Many of the younger centres are typically surrounded by aprons of lava with stony rise topography. The earlier basalt flows have well-developed or evolved soil and are weathered and eroded to an undulating landscape. The younger flows have the characteristic blocky, rugged stony rise topography associated with well-preserved volcanoes such as Mt Napier, Mt Eccles and Mt Rouse. Younger flows are often found filling valleys which had been incised into earlier flow landscapes. Given the long history of eruption, and the high degree of activity in geologically recent times, further activity seems possible, and even likely, so the volcanic province as a whole may be referred to as 'dormant', rather than extinct.

THE MT ROUSE VOLCANO

Mt Rouse is one of many volcanoes in the Western Plains subprovince of the NVP of Victoria. It is situated 240 km west of Melbourne and just 1 km southeast of the town of Penshurst (Fig. 1). Mt Rouse is a composite scoria and lava cone rising approximately 120 m above the level of the surrounding lava fields, and reaching an elevation of 367 m above sea level.

The main scoria cone, with a slope of about 20°, has the form of a horseshoe, encircling the main crater, which is elongated in an east-west direction and breached to the west (Fig. 2). A small ridge of spatter, about five m high and 35 m long, runs along the spur of the scoria cone near the summit of Mount Rouse (Whitehead 1991).

To the south of the main peak is a smaller scoria and ash cone with an almost perfectly-circular 360 m diameter crater rimmed with lava, and inside the crater very steep walls drop 40 m to a semi-permanent lake. The steep sides of this crater indicate that it was partly produced by collapse and the lake lies below the level of the surrounding stony rises. A small

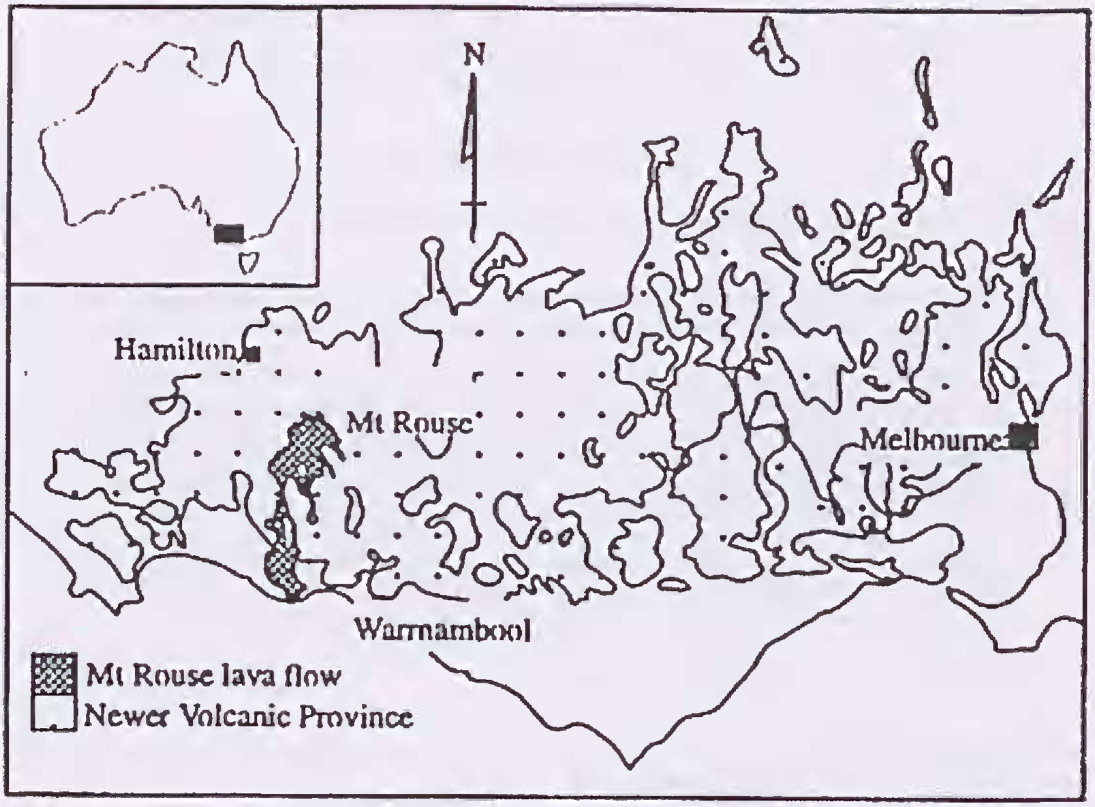

Fig. 1. The Newer Volcanic Province in Western Victoria showing the extent of the Mt Rouse flows (Sutalo 1996).

lava channel to the east on the stony rises lava shield can be traced back to this crater, indicating that it was the source of extensive flows (Sutalo 1996). The vent probably began as a maar eruption, later becoming a lava lake and flow source, before a final collapse or withdrawal of lava produced the deep crater we see today (Fig. 2).

The flows of the Mt Rouse volcano are strikingly different to other flows of the NVP of southeastern Australia because they cover three times the average area, with approximately three times the volume of lava erupted (Joyce & Sutalo 1996). Previously it was believed that the Mt Hamilton flows, originally mapped as a single area of stony rise flows on the Ballarat 1:250 000 map sheet (King 1985), were of twice the average area. However, detailed mapping of this area by MacInnes (1985) has demonstrated the existence of a second major eruption point, Mt Fyans, which produced the southern half of the area of flows originally attributed to Mt Hamilton. Each of these vents, as a result, has an area and volume of eruption from each vent similar to the average for the NVP. Mt Rouse now remains as the single largest lava source in the NVP.

Gibbons & Gill (1964), drawing on earlier work by Gibbons & Downes (1964), described the topography and soils of the Mt Rouse flows as part of a single land-system, the *Girringurrup Land-System*, later renamed the Rouse RTU by Ollier & Joyce (1986), who suggested an age range of two to one Ma for such flows in the NVP. After further mapping of the Skipton & Willaura 1:100 000 map sheet areas, Joyce (1999) suggested a younger age range of 0.2 to 1 Ma for the Rouse RTU.

Gibbons & Gill (1964) said the Mt Rouse flows were characterised by "smoothly-rounded stony rises with infilled swales" and "The difference in height between rise and contiguous hollow varies up to 40 ft, while the distance between rises varies from 50 ft to a few hundred yards". Although the flows are now largely treeless, the original vegetation is believed to have been "a sparse savannah woodland of manna gum and blackwood…or lightwood…on the rises, with a wet tussock grassland of snow-grass…in the swales" (Gibbons & Gill 1964).

The pattern of soils was described by Gibbons &

Fig. 2 Aerial oblique view of Mt Rouse, looking southeast across the main cone, with the smaller crater and lake to the right, and stony rises of the Lava Shield beyond (photo L. K. Elmore ?1960s).

Gill (1964) as a simple catena. "On the rises are thin reddish chocolate soils…with abundant rounded basalt boulders half-buried in the soil and with onion weathering. These soils become darker further down the sides of the rises until, in the swales, they are black, heavy and cracking, sometimes with free carbonate and usually gilgaied…"

The Mt Rouse lava flows have been mainly studied at a regional map scale, apart from the descriptions in Elias (1973), Whitehead (1991), and Ollier (1985). Two distinct ages have been suggested for the Mt Rouse eruption and flows (McDougall & Gill 1975, Ollier 1985, Gray pers. comm. 1996), suggesting the possibility that one or more hitherto unrecognised eruption points exist in this large area of flows. In this study the flows have been mapped in detail for the first time, with additional use of new regolith landform mapping techniques. Published and unpublished dates have been summarised and evaluated, and finally conclusions reached about the physical volcanic history of Mt Rouse.

METHODS

To determine the physical volcanic history of Mt Rouse, detailed mapping for the first time of the long and voluminous Mt Rouse flows has been carried out at a scale of 1:25 000, using recently available State Government topographic maps (Sutalo 1996). Aerial photography at a scale of 1:80 000 has also been used, as well as airborne radiometric and magnetic imagery from the Geological Survey of Victoria. Extensive field work was used to check the mapping, with an altimeter used to measure relative elevations.

This work allowed the detailed description of geomorphological features and the determination of likely mechanisms of formation of flow features. Flow margins are readily apparent in the field, and can be confirmed on magnetic imagery.

A wide range of soils and weathering profiles can be found on lava flows of different ages in Victoria, and these, in conjunction with differences in the geomorphic features of the flows, can be used to map flows into groups according to age. Radiometric im-

Fig. 3. Stony rises of the Lava Shield, looking northeast from Mt Rouse into the morning sun (photo E. B. Joyce 1966).

agery in the standard colour presentation shows the Rouse flows in a red-brown colour, which contrasts clearly with the blues and greens of adjacent older flows, and is also readily distinguished from the bright red of the youngest flows in the NVP, such as Mt Eccles and Mt Napier, to the west. Ollier & Joyce (1986) used a mapping unit called a Regolith Terrain Unit (RTU) which combined descriptions of soils, weathering and geomorphology to distinguish and map discrete terrain units. In other studies, general application of this technique has extended the information available from absolute dating on the Western Plains, and allowed deductions of the way volcanicity has varied through time and across the province, as well as indicating frequency of eruptions, variations in the type of volcano, and the volume of the material produced (Joyce 1999).

These new regolith landform mapping techniques have been applied to several major flows in the NVP, using aerial photographs and radiometric and magnetic imagery e.g. MacInnes (1985) at Mt Hamilton. It is applied here to the Mt Rouse flows for the first time. In addition, flow morphology has been examined, and recent ideas on flow emplacement have been considered (Joyce & Sutalo 1996). A regional search for lava channels and lava tubes or caves which would have acted as feeders was also part of the field mapping.

Lastly, the mineralogy of the flows has been examined using thin sections and X-ray fluorescence spectrometry - XRF (Sutalo 1996) to look for any evidence of variations between flows.

All available published and unpublished dates have been summarised and evaluated.

MT ROUSE AND ITS FLOWS

Well-preserved flows from Mt Rouse form an extensive lava shield around the volcano (Fig. 3). A number of long flows extend beyond the shield, and the Rouse-Port Fairy Flow is one of the longest lava flows in Victoria, extending 60 km to reach the coast (Fig. 4). The lava field area is greater than 450 km^2, three times the average area of other lava fields in Western Victoria. The flows can be divided into two broad areas, connected by narrow lava-filled valleys or channels. One broad area lies immediately south of

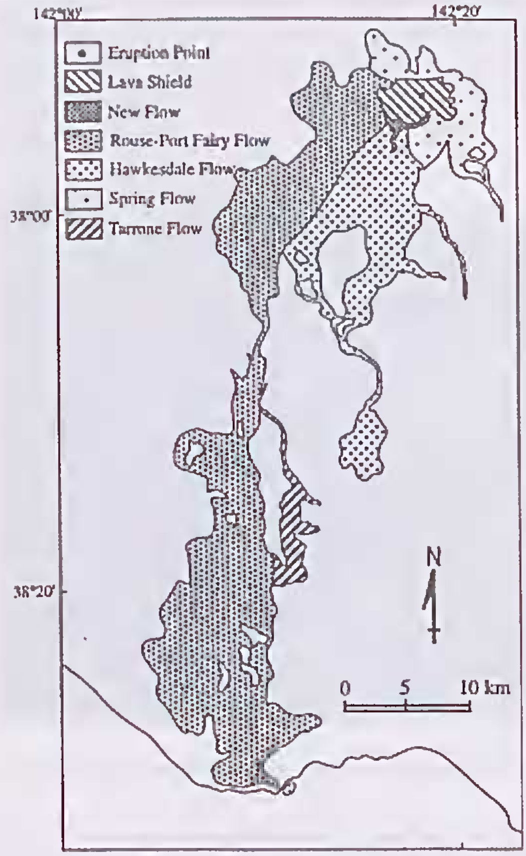

Fig. 4. Distribution of main lava flows from Mt Rouse (Sutalo 1996).

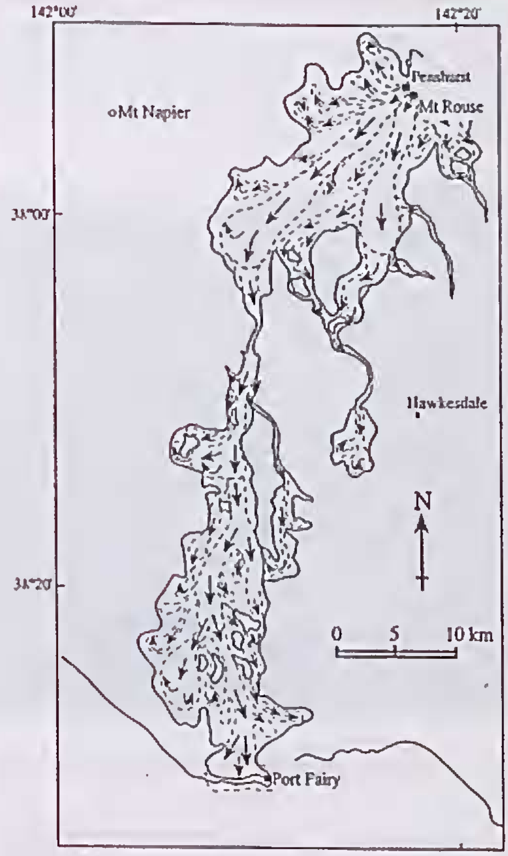

Fig. 5. Interpreted preferred pathways taken by individual lava flows within the Mount Rouse lava field, prior to formation of the Lava Shield and New Flow (Sutalo 1996).

the volcanic cone, and the other lies further south and reaches the coast at Port Fairy (Fig. 5). The characteristic feature of the flows is the irregular, hummocky rises and depressions known in Victoria as 'stony rises' (Skeats & James 1937). Mount Rouse provides one of the best examples of stony rise topography in the NVP.

Natural stream drainage channels on the Mt Rouse flows are rare. Low-lying areas and depressions within the flows form small, ephemeral swamplands, while the tops of stony ridges and flows are well drained. The modern drainage has not yet incised deeply into the Mt Rouse lava field.

Soils and regolith

Sutalo (1996) retained the Mt Rouse flows as a single large Regolith Terrain Unit (RTU), following Ollier & Joyce (1986), but mapped and sub-divided the area of flows into eight smaller RTUs, based on variations in topography, soils, regolith and drainage development. These units reflect the catena concepts in the earlier mapping of Gibbons & Gill (1964).

The distinct RTUs of Mt Rouse flows do not necessarily represent flows of different ages but rather variations in the way individual parts of a single flow sequence were emplaced (Joyce & Sutalo 1996). The aim of the detailed regolith terrain mapping was to help determine the relative sequence of the flows, and in particular decide whether the Mt Rouse flows originated from a single vent producing very large and long flows, or whether the flows were erupted from several vents within the area. The results of the regolith mapping by Sutalo (1996) have been incorporated into Figures 4 & 5.

In the last few kilometres of the flows, near the coast, the regolith cover appears to thicken, and this

Fig. 6. Bare stony surface of a typical flow ridge in the Mt Rouse lava field – hammer for scale (photo E. B. Joyce, as in Sutalo 1996, his Fig. 4.2 p.37)

may be due in part to an addition of sand from the coastal dunes around Port Fairy (Joyce & Sutalo 1996).

Regional topography

The Mt Rouse flows have travelled over gently sloping topography. The slope angle from the base of the scoria cone to the coast is approximately 2.5°. The landscape in general now slopes to the south-west, but the Mt Rouse lava flows cut across this contour trend and flowed more directly south, following pre-existing drainage valleys with this direction. Details of the palaeodrainage of the region are described in Ollier (1985).

The northern and southern parts of the Mt Rouse lava field are broad and flat in nature with lava flows spreading laterally over an extensive plain with only a gentle slope. The central parts of the Mount Rouse lava flows are quite different. Here the southward-slope increases substantially, with about a 120 m drop over a distance of 20 km (Sutalo 1996). Most of the narrow lava-filled valley flows are found in this area. The lava flowing from Mt Rouse travelled more quickly down these pre-existing valleys and in the process formed lava tubes which insulated the lava, allowing it to travel further by cooling more slowly.

The crests of some Mt Rouse flows are up to 15 m higher than those of adjacent but earlier Newer Volcanic flows which form the surrounding plains (Fig. 6). This distinct relief difference is the result of lava flow inflation, which has raised the original flow surface above the level of the valley floor and then further above the level of the original plain. Lava flow inflation is the lifting of the solid crust as broad sheets by the continual injection of molten lava into the interior of the flow (Keszthelyi et al. 1996).

DISTRIBUTION AND CHRONOSEQUENCE OF THE MT ROUSE LAVA FLOWS

Distribution of lava flows

The lava flows of Mt Rouse cover a large area to the east, west and south of the eruption point (Fig. 4).

To the north of Mt Rouse, flows cover only a small area, with the northern edge of the lava flows marked by a small lateral stream, Penshurst Creek, which flows northwest. To the south-east of Mt Rouse two short and narrow flows have travelled down earlier valleys of Spring Creek and Whitehead Creek for several kilometres and subsequently small lateral streams have developed along the flow edges. Further to the west and south of Mt Rouse, stony rise relief decreases, and parallel lateral flow ridges are found towards the centre and along the margins of the flows. It appears the lava has banked up against existing higher topography to the west, and the Eumeralla River is a lateral stream which now marks the western edge of these flows. (For further details of palaeo- and modern drainage, see discussion in Ollier 1985).

The main northern mass of lava flowed southwards and passed through two narrow palaeovalleys. The lines of these valleys are still more or less followed by the modern Moyne River and Back Creek. The Hawkesdale Flow took the eastern Moyne River route. This lava flow branches and rejoins around higher areas of lava which are older than those from Mt Rouse. These areas of higher, earlier lavas surrounded by flows are here called inter-flow 'islands' (also known on Hawaii as *kipuka;* Ollier (1985) used the USA term steptoes). The narrowest sections of these valley flows from Mt Rouse are approximately 100 m wide, and referred to here as 'gates'.

The largest lava flow originating from Mt Rouse is the Rouse-Port Fairy Flow. This travelled through the narrow Back Creek palaeovalley and the flow is less than 1 km wide over a distance of more than 5 km, and at its narrowest the 'gate' is only 400 m wide. This flow widens to the south as it becomes less confined, with the main section of flow averaging 10-15 km in width.

The Tarrone Flow (Fig. 4) is a very distinct flow in a now lava-filled valley. It is most probable that the Rouse-Port Fairy Flow had a break-out or spillover of some kind, producing the Tarrone Flow. It left the main Rouse-Port Fairy Flow, passed through a narrow, 100 m wide 'gate' about 30 km south of Mt Rouse, and continued south along the valley until it ended resting up against the higher elevation margin of its parent Rouse-Port Fairy Flow, some 12 km down slope from where it originated. The diversion of the Tarrone Flow has produced a major inter-flow 'island' 10 km long and 2 to 3 km wide (Fig. 4).

In the last few kilometres of the Rouse-Port Fairy Flow, near the coast, the addition of windblown coastal sand and silt flattens the relief between the stony rises and the depressions, and a separate RTU can be mapped (Sutalo 1996). At the coast itself, the end of the flow is marked by a relatively straight east-west shoreline about 5 km long, and a series of lava tongues extends under the dune-beach system to form shore line 'breakers' (platforms) and reefs. Aeromagnetic surveys over the region indicate that the Rouse-Port Fairy lava flow ends approximately a few hundred metres off the present coast. In contrast, similar airborne imagery over the Mt Eccles Tyrendarra flows to the west of Port Fairy shows magnetic signatures extending about 5 km out to sea, and the dating of Mt Eccles indicates that the sea-level at the time of that eruption was lower than at present. However the coincidence of the present coast and the southern end of the Mt Rouse flows is probably the result of the flows forming a resistant edge to modern coastal erosion, and need not indicate where the sealevel was at the time of the Rouse eruption.

Chronosequence of the Mt Rouse lava flows

The main lava flows recognised in the Mt Rouse lava field are shown in Figure 4. The flows can be placed in a chronological framework using differences between the flows, including distinctive geomorphological features, flow relationships, and sometimes slight differences in mineralogy of the flows. However, it was found that soils do not help with distinguishing individual flows.

The Rouse-Port Fairy Flow

The main Rouse-Port Fairy Flow is the oldest and longest lava flow from Mount Rouse, and extends for a distance of 60 km. The stony rise relief is comparatively low, and generally not more than 5-7 m. Typically honeycomb-textured basalt boulders are embedded in the soil of the stony rises.

The southern part of the Rouse-Port Fairy Flow is interpreted as a single large flow which has divided into two lava flows further down slope, producing as a break-out the Tarrone Flow. Further south the Tarrone Flow splits again, forming three lava tongues and passing around four small inter-flow 'islands'.

Several large distinctive flow tongues of the Rouse-Port Fairy Flow also extend northwestwards from just west of the volcano, for a distance of over 5 km (see Fig. 5). Parts of both of these flows have parallel longitudinal ridges. It is believed that these ridges are remnants of flows which contained lava tubes, and the depressions between the ridges represent areas of collapse. Smaller ridges of the same kind are common throughout the Mount Rouse lava field.

The Spring Flow

The Spring Flow is another early flow which spread to the north and southeast from Mt Rouse, following the course of an earlier Spring Creek for about 6 km and with a total length of 12 km.

The Hawkesdale Flow

The Hawkesdale Flow is the second major flow from Mt Rouse and at 27 km the second longest flow unit. It makes up about half of the eastern side of the lava field. To the south it flows through several narrow 'gates', before stopping about eight km south-west of the township of Hawkesdale (Fig. 5). (It does not reach as far as the Tarrone Flow, as Ollier's (1985) Fig. 2 would seem to indicate). In the west two narrow valley flows leave the main flow, passing around a large 'island' (Ollier's Moorilah Steptoe) and rejoining the main flow further south. Compared to the Rouse-Port Fairy flow, the relief of the Hawkesdale flow is more rugged, with differences in height between stony rises and depressions sometimes greater than 10 m.

The boundary to the northwest with the Rouse-Port Fairy Flow has been inferred, based on differences in relief seen on aerial photographs, and the distribution of stony ridges. Major differences between the two flows are also seen in their narrow valley sectors. The topography of the valley flows of the Rouse-Port Fairy Flow is of wide, flat-topped ridges, usually occurring near the middle of the flows. The narrow lava-filled valleys of the Hawkesdale Flow are comprised of multiple lateral stony ridges with 'collapsed' depressions in between, merging into a single lateral ridge or a series of numerous hump-like ridges (7-12 m high) further to the south.

The Lava Shield

Immediately surrounding the volcano is a low-angle lava shield, which extends for a radius of about 3 km. This lava shield is the youngest of the main flow units. It has a very uneven, rugged stony rise surface of ridges, depressions and hollows (Fig. 2). Relatively fresh, sub-angular to angular boulders and blocks (50-100 cm average diameter) are scattered over the surface. The soil is thin, and mainly confined to cracks between boulders. The relief of the rises is similar to that of the Hawkesdale Flow, but the distance between rises is much less, with rises less than 50 m apart.

It seems likely that the lava shield represents the successive build-up of small lava flows originating from relatively minor eruptions. It is believed that these flows erupted late in the history of Mt Rouse, and the lava shield rests on earlier flows.

A single lava cave was discovered during the mapping of the Rouse flows, with a collapse entrance, rock fall and possible extensions of the cave now below the watertable. About 15 m of flow units are exposed in the walls of the collapse. It has been called Huttons Cave, and lies on the western edge of the Lava Shield about 2 km south of Penshurst (Penshurst South 1:25 000 topographic map 7322-2-S, grid coordinates 612900mE, 580500mN). A plan and cross-section of the cave is given in Sutalo (1996) Appendix 1.

The New Flow

The fifth lava flow group is the New Flow, which consists of a number of small but distinct flows on the south-western edge of the Lava Shield. The flows are approximately 5 km long, and overlie the Hawkesdale Flow, so stratigraphically appear to be recent flows, with a relief of 10-15 m above the other stony rise flows to their east, west and south. Whitehead (1991) traced these flows back through the stony rises of the lava shield to the southern crater of Mt Rouse, making them the youngest of the Mt Rouse flows. Whitehead (1991) stated that the flows emerged from tubes within the lava shield, rather than flowing over the surface of the lava shield, but evidence of lava tubes was not seen in this area (apart from Huttons Cave, further to the north, on the western edge of the Lava Shield.)

EMPLACEMENT OF LONG LAVA FLOWS

Special conditions must have existed for the lava from Mt Rouse to have flowed as far as Port Fairy, 60 km to the south. Only the Campaspe valley flows, at 65 km, exceed the length of the Mt Rouse flows (Coceani 1999). Much work has been done on long lava flows worldwide, to gain a better understanding of processes involved in their formation.

In general, the volume and length of lava flows decreases as the silica content increases (Williams & McBirney 1979). Thus basaltic flows such as those of Mt Rouse are usually more voluminous and longer than high silica rhyolite flows. Walker (1973) analysed the factors affecting the length of lava flows. He considered effusion rates to be the most important controlling factors on lava formation and showed that the distance travelled by a lava flow is proportional to the effusion rate, probably due to the effects of cooling. Lava erupted at higher rates would travel further before cooling lowered its viscosity and inhibited movement. Walker believed that viscosity merely controls the thickness of a lava extrusion, and only indirectly affects the length. Also the effect of the angle of slope of the underlying land surface, though not negligible, is small in relation to other factors.

However, in reality the control of lava lengths is very complex. For instance, effusion rate itself is dependent on a large number of factors: vent shape and dimensions, viscosity, yield strength and magma pressure gradient within the volcano.

Malin (1980) found there to be little support for a direct relationship between flow length and effusion rate in the 87 Hawaiian lava flows he examined. "A statistically more significant relationship exists between flow length and total volume of material extruded" (Malin 1980: 307). However Malin showed that no single factor is most important. Cross-sectional area (probably dependent on the slope, viscosity, and cooling rate), effusion rate, and the total volume all play important parts in the governing of emplacement of lava flows. " One reason for the observed relationship in Hawaii may be that tube-fed flows, with approximately constant cross-sectional area, advanced farther than other types of flows for similar effusion rates and volumes (Malin 1980: 308). It is quite possible that the Hawaiian lava flows would have continued to move many tens of kilometres farther had they not reached the sea".

Atkinson (1990) studied the world's longest lava tube systems, the Undara lava tubes in Northern Queensland - one flow extends over 160 km. It is believed that the flows formed in a very short period of time (a period of three weeks is suggested) and this great length is attributed to a very high effusion rate and favourable topography. Ollier (1985) suggested that the effusion rate might be less important than the continuity of flow in time. Lava tubes will block if an eruption ceases just long enough for the lava to solidify. If the lava is erupted without interruption, it is more likely that a single very long flow is produced, with a lava tube system operating continuously for a long period.

In order to produce a long lava flow the lava must be able to travel a great distance before it cools and freezes. The best way to avoid cooling of lava during transport is by insulating emplacement, as seen in the form of inflation crust rises and lava tube systems. Swanson (1973) indicated that lavas within tubes flowed virtually isothermally, cooling at a rate of only 10^0 C/km. Malin (1980) states, "if flow length were limited by cooling to solidus temperatures, such eruptions could have possibly produced flows as long as 200 km" (p.308), quite sufficient to explain the 60 km Mt Rouse flow.

Hon et al. (1994) studied the emplacement and inflation of pahoehoe sheet flows of active lava flows on Kilauea Volcano, Hawaii. From observations and measurement they established that given sustained lava supply, sheet flows follow a progression from thin sheets to thick inflated flows that are emplaced as a sequence of 'flow lobes'. A flow lobe is the package of lava that is contained within its own crust. Successive sheet-flow lobes remain hydrostatically interconnected and inflate to the same thickness (Keszthelyi 1995).

Hon et al. (1994) concluded that during long-lived eruptions, preferred pathways develop within older portions of the sheet flow that are no longer actively inflating; these pathways evolve into lava tube systems which efficiently deliver lava at velocities of several kilometres per hour to a flow front that may be tens of kilometres away. Keszthelyi et al. (1996) concluded that "long lava flows on the Earth are dominantly (perhaps exclusively) emplaced as inflation pahoehoe flows".

Lava crust inflation mechanisms can be used to explain the development of the Mt Rouse lava flows. Over time lava inflation sheets may develop one or more lava tube systems following preferred pathways, especially in confined valley flows. Observations of aerial photographs and field-based geomorphology studies have enabled reconstruction of the preferred pathways taken by individual lava flows within the Mount Rouse lava field (Fig. 5).

The best evidence found to indicate the presence of lava tubes in the Mount Rouse lava field is Huttons Cave, discovered and mapped during this study. This 14 m deep collapsed lava tube is found 2 km west of the scoria cone, on the edge of the lava shield (Sutalo 1996, Appendix 1: 64). There is no evidence at the surface of any ridge extending over the cave - rather the cave underlies later lava flows. Water-filled cavities in the bottom of the east and west walls of the cave are interpreted as the drainage pathway of a lava tube leading away from the volcano. Huttons Cave is very similar in appearance to the Byaduk lava caves of Mt Napier, which are collapsed lava tubes (Ollier & Brown 1965).

The Mt Rouse flow was a lava crust inflation and tube-fed flow, as is indicated by its length and its surface morphology, with stony rises and low depressions which are possibly inflationary and compressional features, and many large, paired and lateral stony ridges (indicative of collapsed lava tubes or lava sheets). The flows were probably emplaced in a short time, perhaps only weeks. The fluid nature of the lava flows is indicated by the apparent ease with which the lava has several times divided into flows which continued further down slope, travelling through narrow 'gates', and passing around such obstacles as 'islands' composed of remnants of higher and older lava flows.

MINERALOGY

The Mt Rouse basalts are alkali basalts and are petrographically remarkably similar along the 60 km length of the flows. An excellent example is provided by the Tarrone Flow, which is a branch flow fed from the main Rouse-Port Fairy flow (Fig. 4) and shows little variation from the parent flows to its north, being indistinguishable from them both in hand specimen and thin section. Thus it is appropriate to describe a single, general basalt type. (Note however that the lava flow sub-divisions shown in Fig. 4 are based on geomorphological features and do not imply or require significant petrographic differences.)

Hand specimens of basalt collected from the surfaces of the flows are vesicular (10-15% range) with some vesicles up to 1.5 cm in length. Fresher samples are granular, dark-grey to grey-blue in colour, and very fine-grained with vesicular texture. Small phenocrysts of plagioclase and light green olivine can be seen in hand sample, with small phenocrysts of blue-black clinopyroxene visible in the groundmass in some cases. In most samples the green colour of fresh olivine has been altered to a brown-yellow, and feldspars have altered to a white clay, making them conspicuous in hand specimen. Calcite, zeolite minerals and limonite (a combination of Fe-oxides – goethite and hematite - and clays) often form in the vesicles.

In thin section, the Mt Rouse basalts have a fine-grained interlocking matrix, with crystals seldom greater than 1 mm. The most abundant mineral is plagioclase, which is approximately 50% of the rock. It occurs as lathes, which have a maximum size of 1.3 mm long with an average of 0.5 mm, and also interstitially. These lathes preserve well-defined multiple twinning unlike anhedrally-shaped strongly-zoned crystals that display ill-defined twins with strong undulose extinction.

Clinopyroxenes as mostly fine grains make up about 20% of total rock composition and are disseminated throughout the groundmass as fine subhedral crystals. Phenocrysts are found in the southern flows near the coast, and also in the northern areas, especially in the lava shield, but make up only a few percent of the total amount. Olivine is about 15% of the rock composition with grains averaging approximately 0.5 mm in length. Most of the samples collected show very little evidence of alteration except for partial alteration of olivine to a translucent, reddish-brown iddingsite, mainly concentrated on the outer edges of and along fractures in the olivine grains. The primary opaque minerals in the Mt Rouse basalts are magnetite, commonly occurring as small square-planar minerals, and lesser ilmenite.

The incompatible trace elements for Mt Rouse show close similarities to those of alkali ocean island basalts (OIB), i.e. enriched in the more incompatible elements, and depleted in elements chemically similar to the heavy rare earths (i.e. Y). The Mt Rouse alkali basalts are typical intraplate magmatic rocks. The close similarities between samples from different parts of the Mt Rouse flow are consistent with these rocks representing a single magmatic unit, and fed from a single magma chamber at depth.

DATING OF THE MT ROUSE LAVA FLOWS

The degree of weathering and soil formation can be used to estimate the relative age of the Mt Rouse lava flow, and of the surrounding earlier lava flows from other volcanoes. The earliest flows on the Western Plains, dated by K/Ar at 4.5 Ma, show deep kaolinitic profiles with mottling and occasional ironstone development, and suggest the effects of late Tertiary hot and wet climate. Flows of intermediate age (1-3 Ma) have one to two metres of brown clay soil and form a level, relatively stone-free plain, with well-developed gilgai. Flows of less than 1 Ma, many of which are late-Quaternary in age and some less than 20,000 B.P., have well-preserved flow surfaces and little or no soil cover, and are associated with lakes and swamps due to disrupted drainage (Joyce 1999). These young flows show the stony rise topography characteristic of Mt Rouse, Mt Napier and Mt Eccles, and other areas of long and voluminous flow on the Western Plains.

Overall the geomorphological and regolith evidence suggests a young age for the Mt Rouse flows, and this is supported by K/Ar ages for four samples from the Mt Rouse-Port Fairy flows, to the south near Port Fairy, where McDougall & Gill (1975) obtained ages of 0.312±0.005 Ma, 0.301±0.008 Ma, 0.404±0.017 Ma, and 0.438±0.007 Ma. Using more recent decay constants, Ollier (1985) re-calculated these figures to 0.320 Ma, 0.309 Ma, 0.415 Ma, and 0.450 Ma respectively.

New dates for lava flows immediately south of Mt Rouse have been obtained by Gray (pers. comm. 1996), with ages of 0.35 Ma and 0.32 Ma for basalt samples from the upper section of the Hawkesdale Flow, some 20 km south of Mt Rouse. These ages are consistent with the ages (above) reported for flows near Port Fairy by McDougall & Gill (1975).

Ollier (1985) found that the pyroclastics of the scoria cone at Mt Rouse were unsuitable for isotopic dating, but he obtained a date for a single, fresh-looking lava flow interbedded with the eastern scoria margin of the deep southern crater. The sample, which would seem from field relationships to be part of the Lava Shield flows and so part of the final stages of the Mt Rouse activity, gave an age of 1.82±0.004 Ma. Generally the K/Ar method of dating has been found unsuitable for the lavas of the Mt Rouse flows because they are vesicular and often partly weathered. Ollier (1985) was careful to point out that his single sample was fresh and unaltered in appearance and hence suitable for K/Ar dating.

Discussion of dates

Throughout the NVP the formation of pyroclastic scoria cones is associated with the last stages of volcanism (Joyce & Sutalo 1996). The interbedding of the lava flow with scoria implies that the date obtained by Ollier (1985) is late in the volcanic history of Mt Rouse. McDougall & Gill (1975) maintain that it is unlikely that the ages they obtained near Port Fairy are too old, but do not discuss the possibility of them being too young. The 1.5 Ma difference between the dates for the coastal flows and upper Hawkesdale flows, and the flow interbedded with scoria at Mt Rouse dated by Ollier, suggests that: (i) there are two flows and thus two distinct periods of high volcanic activity; (ii) the flows dated south of Mt Rouse and near Port Fairy are not from Mt Rouse but from a second or third source; or (iii) the discrepancy in dates must be attributed to an error in the dating of the sample obtained by Ollier.

The Mount Rouse basalts are very distinctive compared to the nearby flows of the basalt plains, and the flow boundaries have now been closely mapped. No volcanic vents have been found in the vicinity of Port Fairy that could be an alternative source for the flows dated by McDougall & Gill. The RTU mapping and flow mapping in the field described in this paper indicate that the lava flows dated by McDougall and Gill near Port Fairy and by Gray nearer Mt Rouse are all from Mount Rouse. Geomorphic and regolith relationships over the entire flow suggest that two distinctive periods of eruption for Mt Rouse are unlikely. It is concluded that the age obtained by Ollier is not correct. On the other hand the consistency of the dates obtained by McDougall & Gill (1975) near Port Fairy, and nearer to Mt Rouse by Gray (pers. comm. 1996), suggests they are more reliable, and all the Mt Rouse activity took place some 0.3 Ma ago.

Eruption sequence

1. Large volumes of very fluid lava were extruded from the Mt Rouse volcano to form the major Rouse-Port Fairy Flow. Lava inflation sheets formed the broad lava fields to the west and south-west of the eruption point, and lava of the Spring Flow flowed down the short Spring Creek valley to the east and south.
2. Overflow from lava sheets of the Rouse-Port Fairy Flow sent flows down narrow pre-existing stream valleys, lava tubes developed, and fed the flows, and lava reached the coast at Port Fairy, 60 km south of the eruption point.

3. The Tarrone Flow branched from the central section of the Rouse-Port Fairy Flow and followed a narrow stream valley, passing around a large inter-flow 'island,' and stopping 12 km further down slope up against the margin of its higher elevation parent flow.
4. Further extrusion of lava from Mt Rouse produced the major Hawkesdale Flow, which branched down a number of pre-existing stream valleys, forming many inter-flow 'islands'. The flow stopped short of rejoining the main Rouse-Port Fairy flow, due to ridges of older stony rise topography (not from the Mt Rouse volcano).
5. The main scoria cone was built by fire-fountaining, and ash fell on the plains to the north and northwest.
6. A new eruption centre was formed to the south of the main cone, perhaps initially by maar eruption, and a scoria-rimmed lava lake overflowed along a lava channel to the east of the crater, producing the Lava Shield unit, built up of successive small lava flows, and burying any previous flows.
7. Further flows, mapped here as the New Flow, spread southwards beyond the southern margin of the lava shield, fed from tubes within the lava shield.
8. Ash and scoria erupted from the new crater, burying the lava channel (6) on the crater rim, and finally subsurface withdrawal of lava from the lava lake produced a deep pit crater.
9. The pit crater developed a shallow lake.

CONCLUSIONS

Mt Rouse erupted about 350,000 years ago. The basaltic lava flows of Mt Rouse are the longest in Western Victoria, covering a distance of 60 km from north to south. The stony rise topography of the lava flows shows that lava sheet inflation and associated lava tube systems provided the mechanisms for long lava flow development. Emplacement of the flows probably occurred relatively quickly, possibly over a period of a few weeks to a few months.

Detailed mapping has shown that more than one eruption point is unlikely. There is no alternative source for the near-coastal basalts near Port Fairy, and all the mapped flows apparently originated from Mount Rouse. (The basanite dome of Whitehead (1991) six km southwest of Mt Rouse, does not appear to be directly related to the Mt Rouse eruption, showing no obvious flow contribution to the Mt Rouse flows, and may be a separate volcano of older age). The distinct homogeneity in petrography and geochemistry for all the Mt Rouse basalts, and the geomorphology and regolith of the flows, strongly support the conclusion that Mt Rouse was the eruptive centre for all the flows.

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